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AN ELECTRON-BEAM-TRIGGERED SPARK GAP

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Abstract

Studies on the triggering of a high-voltage, gas-insulated spark gap by an electron beam have been conducted. Risetimes of approximately 2.5 ns and subnanosecond jitter have been obtained for 3 cm gaps with gap voltages as low as 50% of the self-breakdown voltage (variable to 1 MV). The switch delay (including the diode) was 50 ns. The working media were N_2, and mixtures of N_2 and Ar, and of N_2 and SF_6 at pressures of 1-3 atm. Open shutter photographs show that the discharge is broad in cross-section.

Voltage, current, and jitter measurements have been made for a wide range of gap conditions and electron-beam parameters. Variations in the character of the discharge have been inferred using streak and open shutter photography. Correlation between electron beam width, beam energy, discharge channel width, current risetime, delay, and jitter are discussed.

Introduction

Several current high priority research efforts such as fusion, the production of high energy-particle beams, and the simulation of environments associated with nuclear weapons detonations, require the generation of very high voltage, high peak power pulses. One of the principle pre-requisites to achieving this objective is the development of switches that will allow fast transfer of energy from an energy storage system to the load or transducer. We are currently engaged in a research program designed to improve the physical understanding of switching processes for the subsequent development of an advanced, low inductance, fast rise time, command fired spark gap switch, capable of operating at very high voltages (MV). Encouraging results toward this goal have been achieved by laser triggered switching [1] (LTS), and by e-beam triggered switching [2,3] (EBTS). This paper discusses an investigation into e-beam initiated breakdown which leads to the formation of a volume discharge (proportional to the cross-sectional area of the injected beam), which helps reduce electrode erosion and switch inductance.

The Experimental Arrangement

The experiment consists of an energy storage element, a gas insulated, pressurized spark gap, and a source of energetic electrons. (Fig. 1). The energy storage element and the spark gap are both contained within the high pressure vessel of the Ion Physics Corporation FX-15 (Fig 2). The energy storage element is a Van de Graaff charged co-axial line. It is capable of producing a 1 MV rectangular pulse of approximately 10 ns FWHM duration. The spark gap is formed by an interruption in the center conductor of the line. The stainless steel electrodes have a Bruce profile and are 21.5 cm in diameter. The high pressure in

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sulating gas also serves as the dielectric for the co-axial line. The electron beam is generated by a cold cathode, field emmission vacuum diode, which is located behind the grounded electrode. It is actually placed inside the inner conductor of the output co-axial line, so as to introduce the e-beam axially through a 1" diameter aperature in the center of the electrode. In order to maintain a uniform field distribution in the gap and to protect the foil from the discharge, the aperature was covered with a stainless steel mesh (0.050"). The diode[4] (Fig. 3), designed and built at Texas Tech University, utilizes a spiral groved graphite cathode, and a thin foil anode. Graphite was chosen because of its fast "turn on" properties[5]. The diode was designed to have an impedance of 70 Ω to match that of the driving generator. This generator is a 25 stage modified Marx pulse forming network (Heds pulser)[6]. It combines the voltage multiplicative feature of the standard Marx circuit with the pulse shaping characteristics of a lumped parameter network. The sequence of events in the experiment is as follows: The Marx erects to give an output waveform characterized by a 250 kV trapezoidal pulse of 50 ns FWHM duration with a 4 ns risetime. This pulse propagates down a 70 Ω, oil-filled, co-axial transmission line and appears across the anode-cathode gap of the diode. The diode emits, through a 2 mil. titaminan foil, a 1.5 kA, 200 keV burst of electrons with a 0-50% risetime of 1.5 ns and a duration of 15 ns. This pulsed beam of electrons travels through 1.5 cm of the high pressure gas before it enters the spark gap. The insulating gas is ionized by electron impact, resulting in the subsequent formation of an ionized conduction path and the collapse of the voltage across the gap. The charged co-axial line of the FX-15 discharges, and the resulting wave propagates down a 50 Ω, oil-filled output transmission line, which is terminated in a matching $AlCl_3$ water resistor. The outer conductor of the Marx Generator to diode transmission line also serves as the inner conductor for the FX-15 output transmission line.

Experimental Approach

The characteristics of the spark gap breakdown investigated were: (1) the risetime of the transmitted voltage pulse, (2) the switch delay and jitter, and (3) the spatial character of the breakdown. The diagnostics used were open shutter and streak photography to record the character of the discharge, and a capacitive divider probe (C_1), located in the FX-15 output transmission line, to monitor the voltage pulse generated at breakdown.

The parameters that we varied during the course of our investigation include: (1) The gap polarity (depending on how the Van de Graaff was charged, the target electrode was either positive or negative. When charged positive the injected e-beam was accelerated by the initial electric field in the gap, and for the target electrode negative the beam was decelerated), (2) the gap voltage V_g (V_g was varied between 50% and 98% of the self-breakdown voltage which ranged from 75 kV to 400kV),(3) gas pressure (1-3 atm), (4) the type of gas (N_2, mixtures of N_2 and Ar, and mixtures of N_2 and SF_6), (5) the e-beam diameter (1.25 cm and 2.50 cm), and (6) the e-beam energy (150 keV to 250 keV).

Results

The pulse risetime was observed to vary with the beam energy and ranged from 2.5 to 3 ns. The larger value was obtained for a beam energy of 150 keV and V_g = 100 kV or, 50% $_{VSB}$. The jitter was found to be virtually identical throughout the range of our investigation. Fig. 4a is representa tive of all jitter measurements. There are 15 separate, superimposed traces of the voltage pulse as monitored by the capacitive probe (C_1), and displayed on a Tektronix 519 oscilloscope. The scope was triggered with the signal from the $\dot{B}$ probe ($\dot{B}_1$) located on the diode transmission line. The sweep speed was 2 ns/div, thus, the resolution is approximately 0.2 ns and the jitter can be seen to be no greater than this amount. These traces correspond to breakdown of a 3.2 cm gap in N_2 at 3 atm. The gap voltage was V_g = 235 kV or 94% V_{SB} The self-breakdown voltage was 250 kV. The traces in Fig. 4b are further examples of the excellent jitter characteristics. With all other parameters identical to those given above, the beam was injected when V_g = 130 kV or 52% V_{SB}. Again, the jitter was below the capabilities of our resolution. These two experiments were conducted for positive and negative polarities, yielding identical results. The delay was obtained from figure 5 (a-e), where the $\dot{B}$ signal from the diode transmission line is delayed to appear after the FX-15 voltage pulse. The delay time was measured to be 52 ns in pure N_2, which is consistent with previous studies[3]. The figure also demonstrates that (for these low voltages and pressures) the delay was invariant to both the pressure and the gap voltage (as a function of the self-breakdown voltage). We should also note that these results were obtained with a DC charged gap; one would expect the performance to be better for a pulse charged gap.

The character of the gas discharge for e-beam initiated breakdown was determined from open shutter photographs. This is shown in Fig. 6a when the target electrode was charged positive and in Fig 6b for a negative charged electrode. These two photographs are representative of the spatial character of the discharges observed throughout the range of our investigation. For the same polarity, the light intensity varied as we changed experimental characteristics. For different polarities, the character of the light emission are different, indicating that there is probably a difference in the breakdown processes. Note that for both cases, the breakdown takes the form of a volume discharge. No localized spark channels were seen.

Fig. 7 demonstrates the variation of the discharge as a function of the e-beam diameter. Note that the volume of the discharge is proportional to the cross-sectional area of the injected beam.

Fig. 8 depicts the variation in the dimensions of the discharge cross-section as a function of the energy of the injected beam. The light intensity is seen to be significantly increased when a more energetic beam is introduced into the gap. To investigate the significance of this observation, voltage pulses for varying e-beam energy were recorded (Fig. 9). The amplitude of the pulse is also observed to be a function of the beam energy. These results indicate that the degree of ionization in the discharge plasma, hence the resistivity varies with the beam energy. The voltage drop across the gap is, therefore, a function of the e-beam energy.

Streak photographs of the discharge are shown in Fig. 10. Again, we can observe a difference between the cases of positive and negative target electrodes in the gap. Preliminary analysis indicate that the early emission of light corresponds to the actual breakdown (the time duration is the same as the voltage pulse), and the second emission is the result of the recombination process. Further analysis of these observations are presently being made.

Conclusions

The results obtained in this series of experiments on e-beam triggered switching are summarized as follows: (1) fast risetime (2.5 ns), (2) low jitter (less than 0.2 ns for $V_g \geq 50\%\ V_{SB}$), and (3) volume discharge. The characteristics make e-beam triggered switches highly desirable for many applications.

The risetimes of the self-breakdown and the triggered voltage pulses were virtually identical, as demonstrated by the superimposed traces shown in figure 11. This is due to the fact that the pulse risetimes were generator limited rather than spark gap limited.

The demonstrated low jitter (particularly when operated at voltages well below the self-breakdown voltage), is one of the most significant contributions of this work. Small jitter is crucial to the successful operation of any pulse power system, however, it becomes extremely critical in any scheme that utilizes the simultaneous discharge of parallel pulse forming lines into a common load. Prefires can be virtually eliminated, due to the ability of the switch to function reliability at low voltage levels. The diode and, therefore, the switch has a very good single shot reliability, which eliminates most misfires.

The EBTS breakdown was observed to take the form of a volume discharge (proportional to the size of the injected beam). This large area breakdown offers several advantages over the narrow channel breakdown found with most switches (e.g. LTS). These are: (1) The EBTS can be scaled up to very large area electrodes and transmission lines while maintaining a low switch inductance (a particularily attractive concept is an annular geometry), whereas other switches cannot duplicate this, unless multiple, current-sharing channels are formed. This, however, is not easily accomplished. In LTS, for example, multiple channels can be triggered by geometrical beam spliting[1], but this method has optical alignment and maintenance problems particularly on large systems. This problem however, can probably be circumvented by the use of fiber optics[7]. (2) The volume discharge should result in a substantial lowering of the switch inductance[4], hence, faster risetimes. (3) The volume discharge minimizes electrode erosion, thereby enhancing the switch lifetime and thus promoting the possibility of developing a reliable rep-rated EBTS. The recovery time should also be reduced as contrasted to the narrow channel discharge case because of the lower degree of ionization per unit volume.

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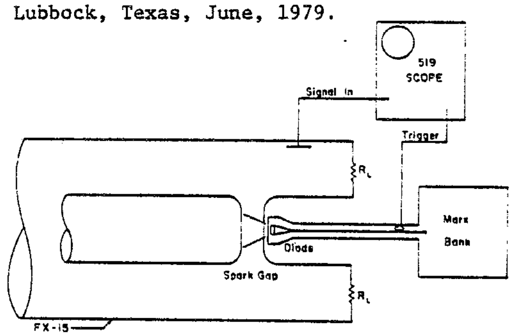


Figure 1: Basic Arrangement

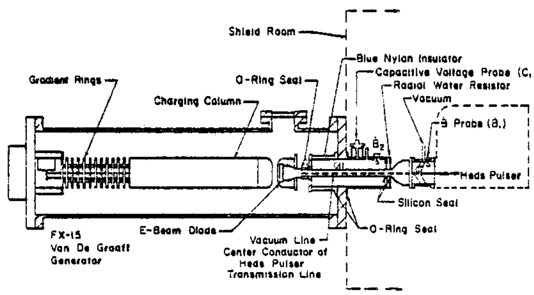


Figure 2: Experimental Arrangement

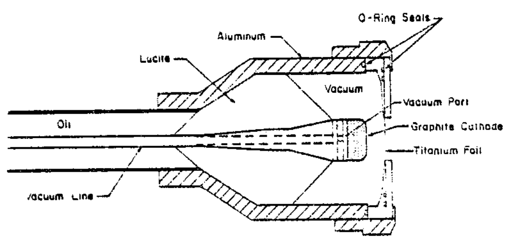


Figure 3: The Diode

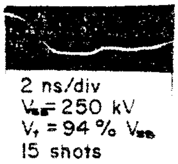


Figure 4a

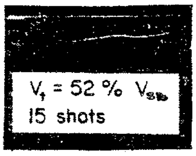


Figure 4b

Fig. 4 Jitter

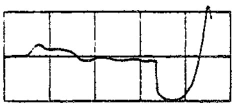
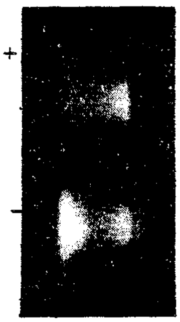


Figure 5: Delay



2.5 cm

\+ −

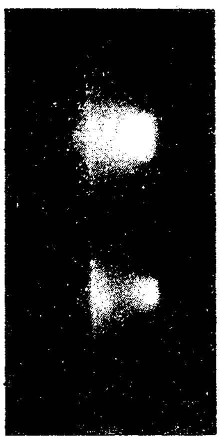
a: Positive Target Electrode

← e-beam

− +

b: Negative Target Electrode

Figure 6:
Variation is the open shutter photographs of the discharge as a function of the polarity of the target electrode

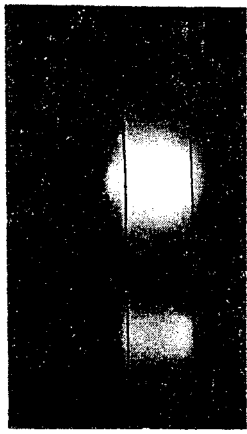


\+ e-beam dia. = 2.50 cm

← e-beam

\+ e-beam dia. = 1.25 cm

Figure 7:
Variation in the open shutter photographs of the discharge as a function of the e-beam cross-sectional area



Spark Gap Electrodes

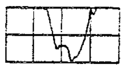
E = 200 keV

← e-beam

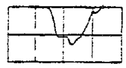
E = 75 keV

Figure 8:

Variation in the open shutter photographs of the discharge as a function of the e-beam energy



$E_p \simeq 200$ keV

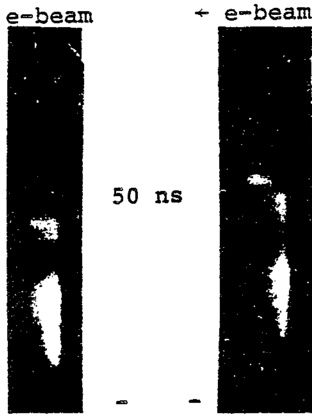


$E_p \simeq 80$ keV

Figure 9:
Pulse Amplitude as a Function of the E-Beam Energy

← e-beam ← e-beam

Streak Streak



\+ − − +

Figure 10a Positive Case

Figure 10b Negative Case

Fig. 10
Streak Photographs of E-Beam Initiated Breakdown

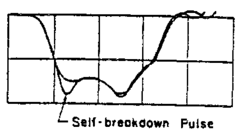


Figure 11:

Superimposed self-breakdown and e-beam initiated breakdown voltage pulses